Optimizing Energy Savings from Direct DC in U.S. Residential Buildings

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Robert Van Buskirk and Chris Marnay

Direct DC Power Systems for Efficiency and Renewable Energy Integration with a Residential and Small Commercial Focus

Part of Larger Project with 4 Deliverables

1. 'Catalog' of DC Appliances and Power Systems
2. Evaluation of DC Network Systems and Technologies (Marnay)
3. Direct DC Energy Savings Modeling and Forecast
4. Direct DC Power System Research Plan Recommendations

Direct DC Power Systems for Efficiency and Renewable Energy Integration with a Residential and Small Commercial Focus

Part of Larger Project with 4 Deliverables

1. 'Catalog' of DC Appliances and Power Systems

↓

3. Direct DC Energy Savings Modeling and Forecast

Project Context:

- Potential Energy Savings from Direct-DC in U.S. Residential Buildings
  - 30-year national energy savings potential
    - Rapid increase in penetration of building-sited PV
    - → Need for on-site energy storage
  - Relevant context for foreseeable future →

    PV in net-metered houses (not off-grid)
  - Emergence of electric vehicles

Main distinctions between this work and prior studies

1. Energy impacts determined for <u>net-metered</u> system accounting for timing of the load (complexity)
   - Directly determines if DC power is used directly
   - or if AC-grid power must be rectified to supply DC load
2. Includes electricity storage
3. Detailed consideration AC vs. DC end-uses
4. Clearly distinguishes energy savings from
   - increased adoption of DC-based technologies (which can be run of AC or DC) versus
   - direct-use of DC power

Modeling Outline

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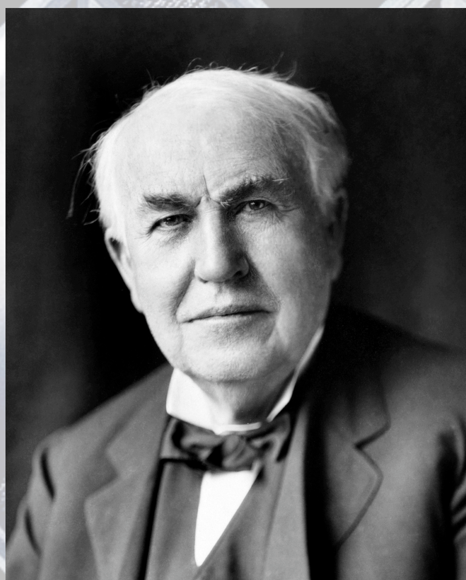
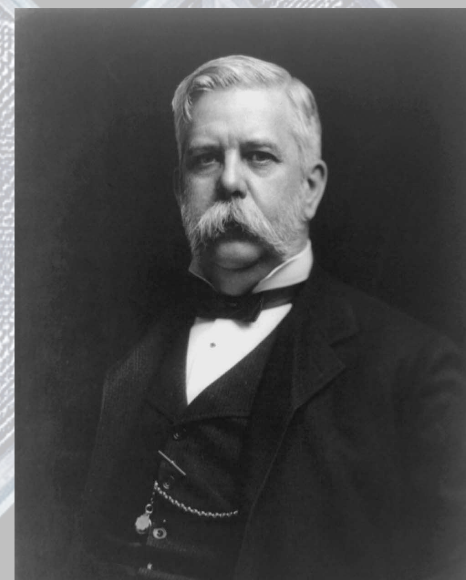
BATTLE of the Currents

Edison



Westinghouse



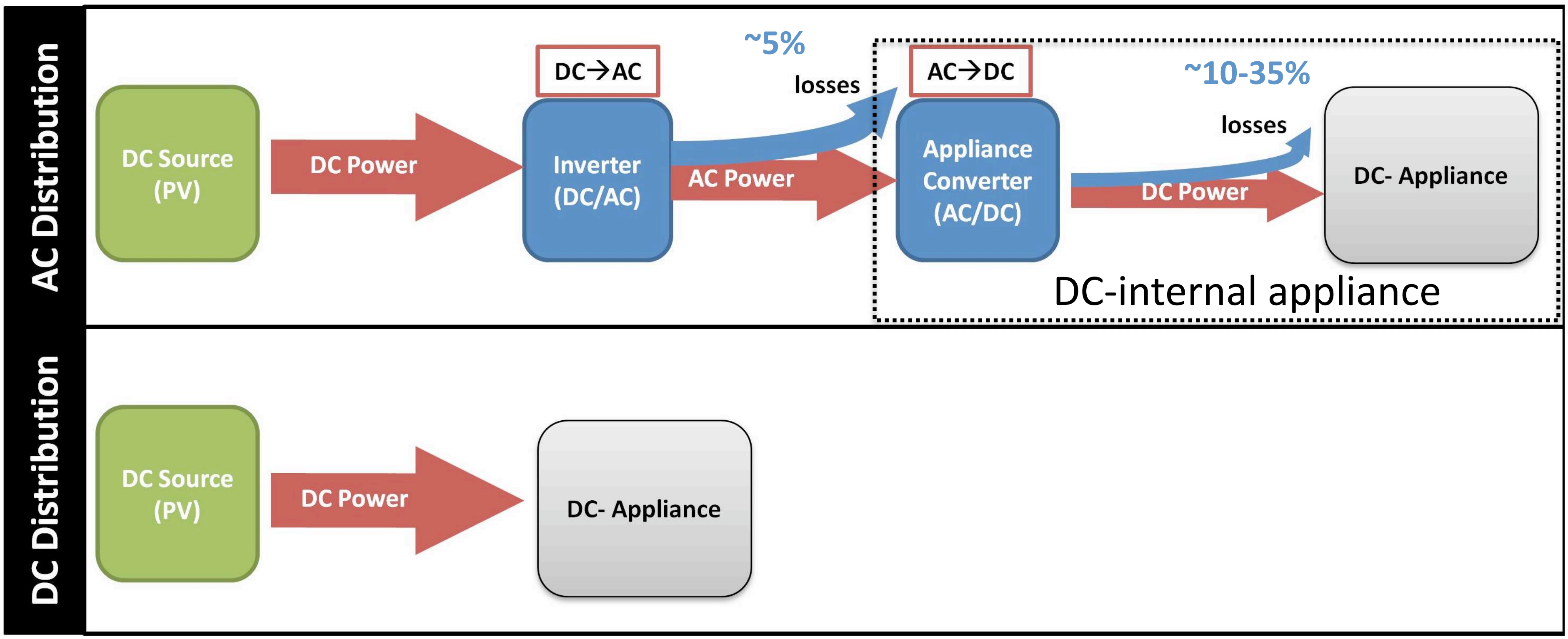
First power systems were based on DC

DC was Implemented with small, distributed power plants

AC enabled long distance power transmission

What is "Direct-DC"?

Providing power *directly* from a DC source to end-uses



But not that simple in real houses.

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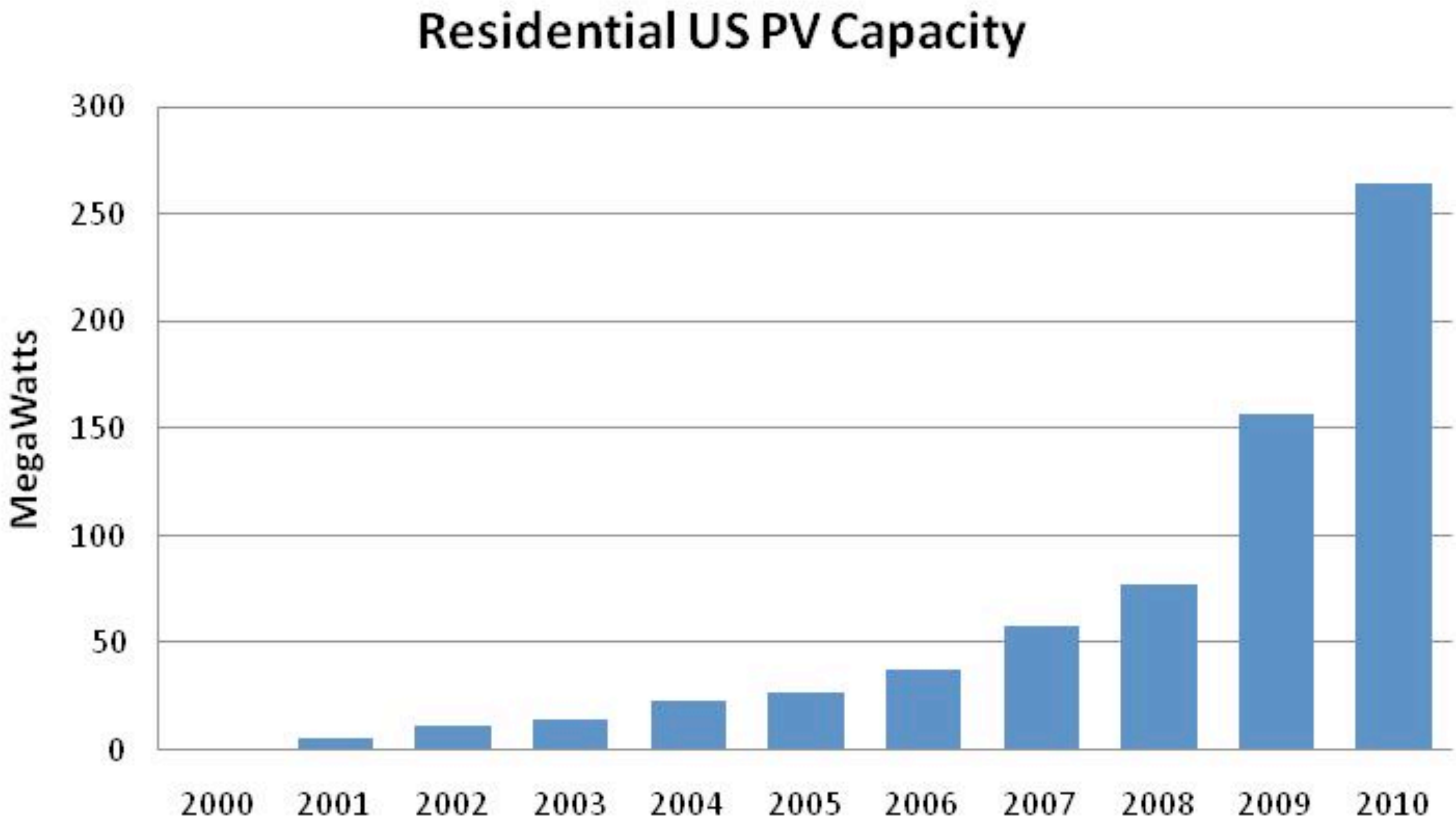
1. Increased use of DC products

- **DC-internal products (currently run on AC), among most efficient on market**
  - Consumer electronics
  - Electronic lighting
  - DC motors (brushless), especially with variable speed drives
- **And Electric Vehicles (DC)**
  - Nissan Leaf, Chevy Volt, Tesla Roadster

2. Rapid increase in U.S. residential PV installations

- >20% yearly growth rate between 2000-2010
- Other renewable DC sources: Small Wind, Micro Hydro (<5% of market share)



3. Emergence of DC power standards

- EMerge Alliance: 24V standard, 380V coming
- Products that meet the EMerge 24V standard:
  - Ceiling suspension system enables DC distribution without additional wiring (Armstrong)
  - Direct-DC lighting with PV (Nextek Power Systems)

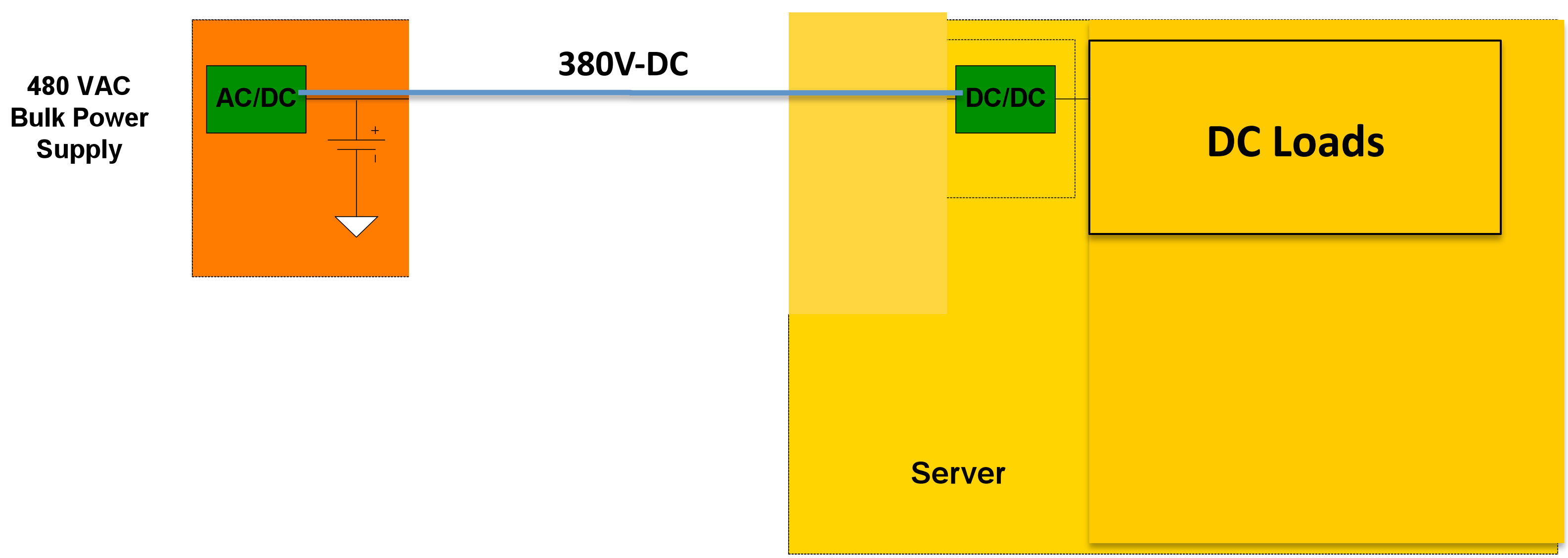
EMerge™ ALLIANCE

NEXTEK Power Systems Inc.

4. Demonstrated energy savings in DC data centers

(Ton, Fortenbery and Tschudi, 2007)

- **Eliminated DC/AC, AC/DC** conversions between UPS and PSU
- Demonstrated **7.2 – 28.2% energy savings**, depending on system conversion efficiencies



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- Given the uncertainties inherent in fundamentally new technologies, and to determine whether more research is justified, we wanted to estimate:

  - How much energy can Direct-DC save at the house level?
  - How much will it save under different scenarios?
    - Energy storage
    - Shifted house loads
    - Add electric vehicle load
  - Consider effects of
    - climate
    - power conversion efficiencies (AC/DC, DC/AC, DC/DC)

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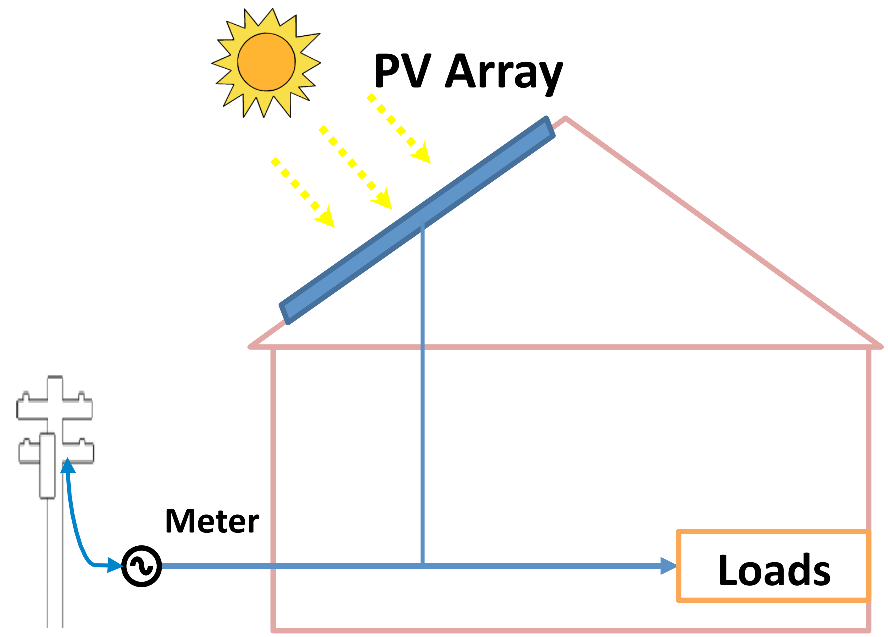
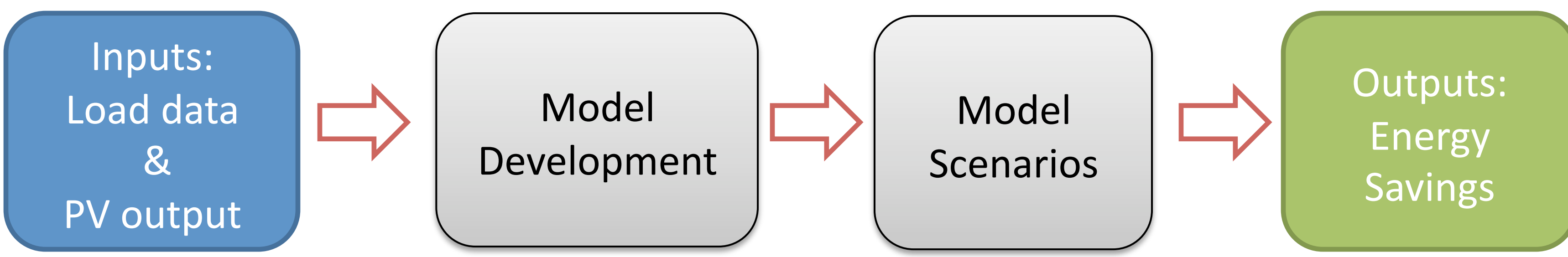
Hypothetical Household:

- Rooftop PV system
- Grid-connected
- With net-metering



Conceptual framework of the modeling:



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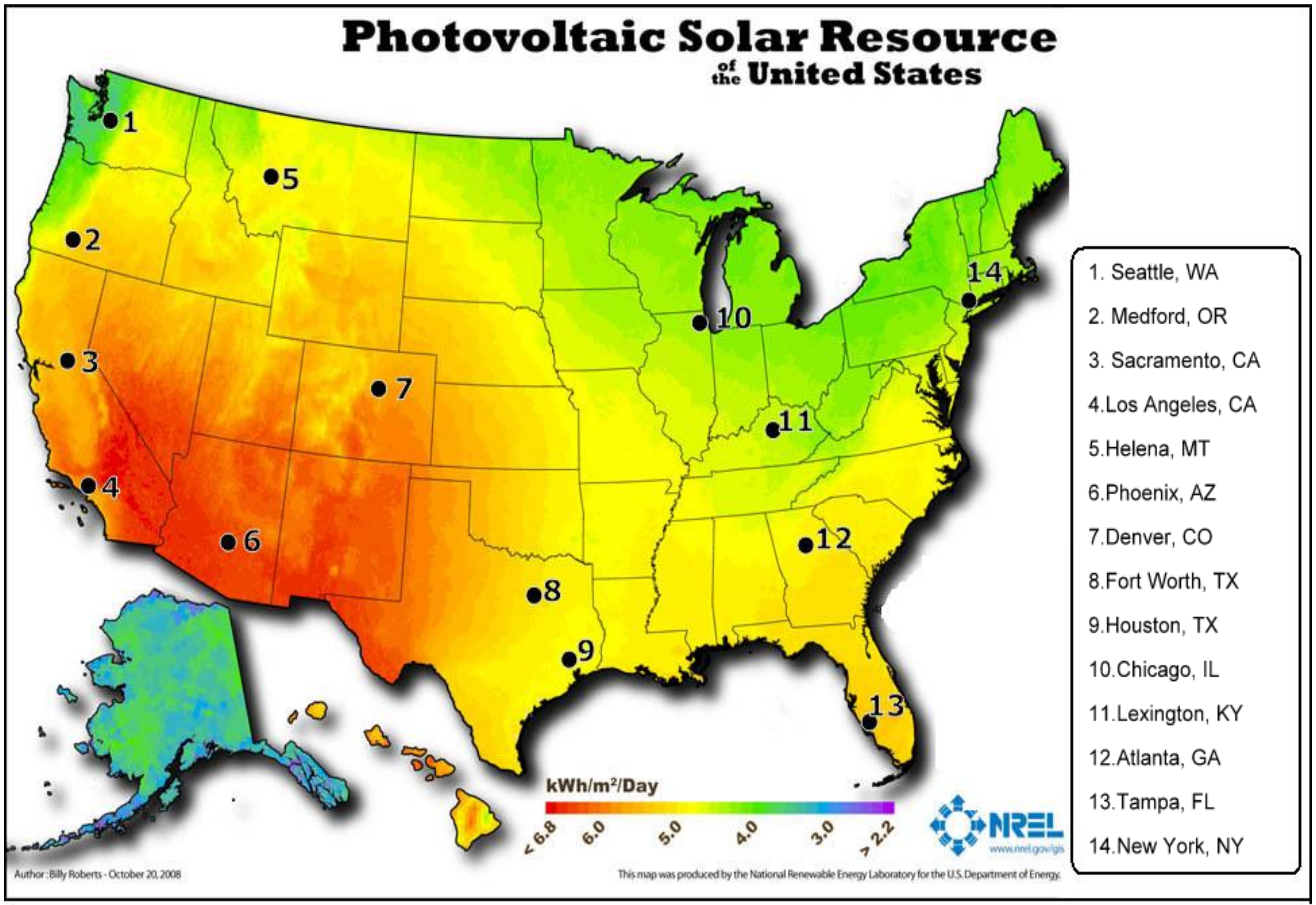
INPUTS: Residential load data (simulated) & PV output data for 14 U.S. cities from NREL's Solar Advisor Model (SAM)

- Both are average hourly data (8760 data points for 1 year)
- Opportunity to test effect of climate



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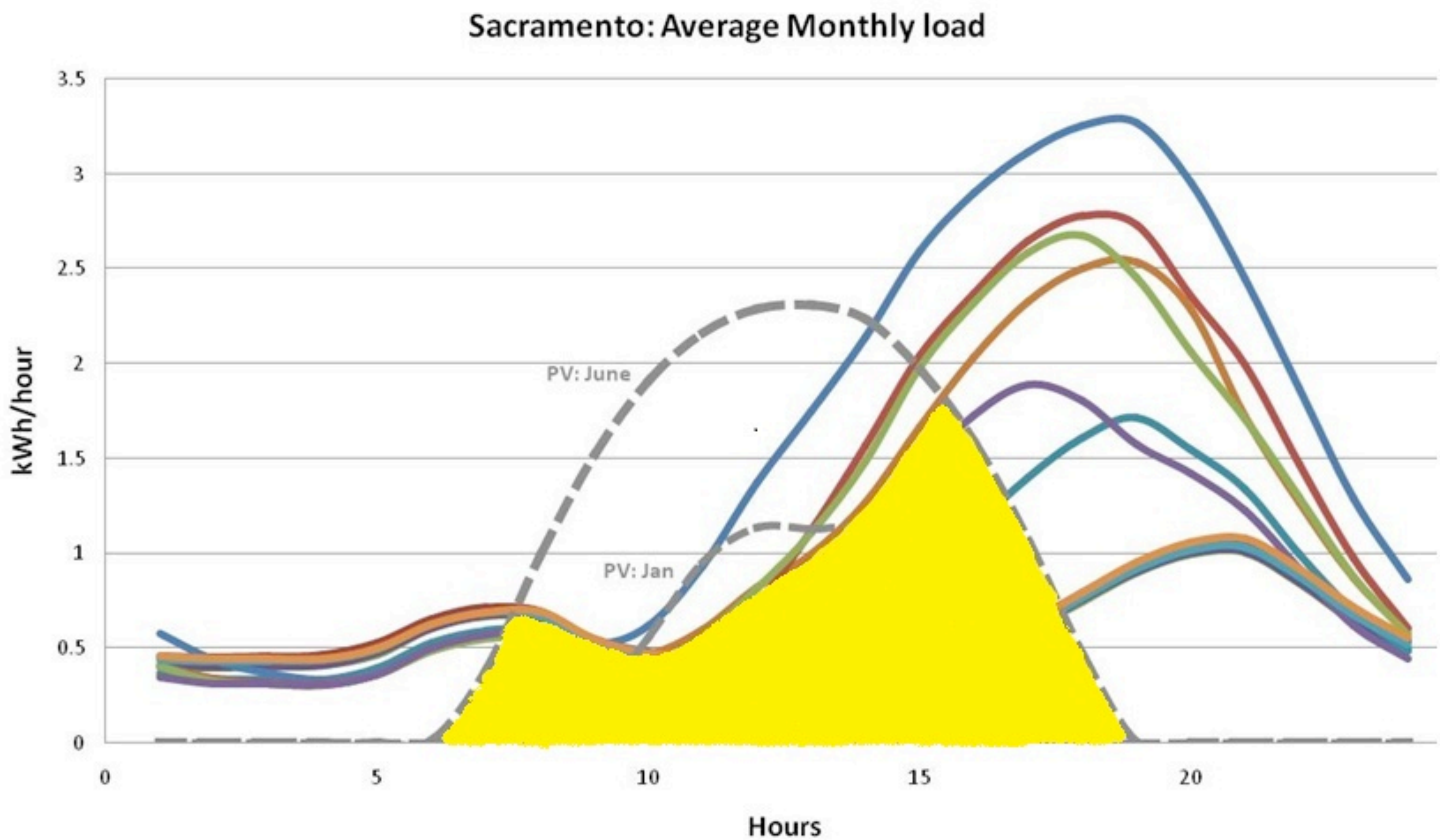
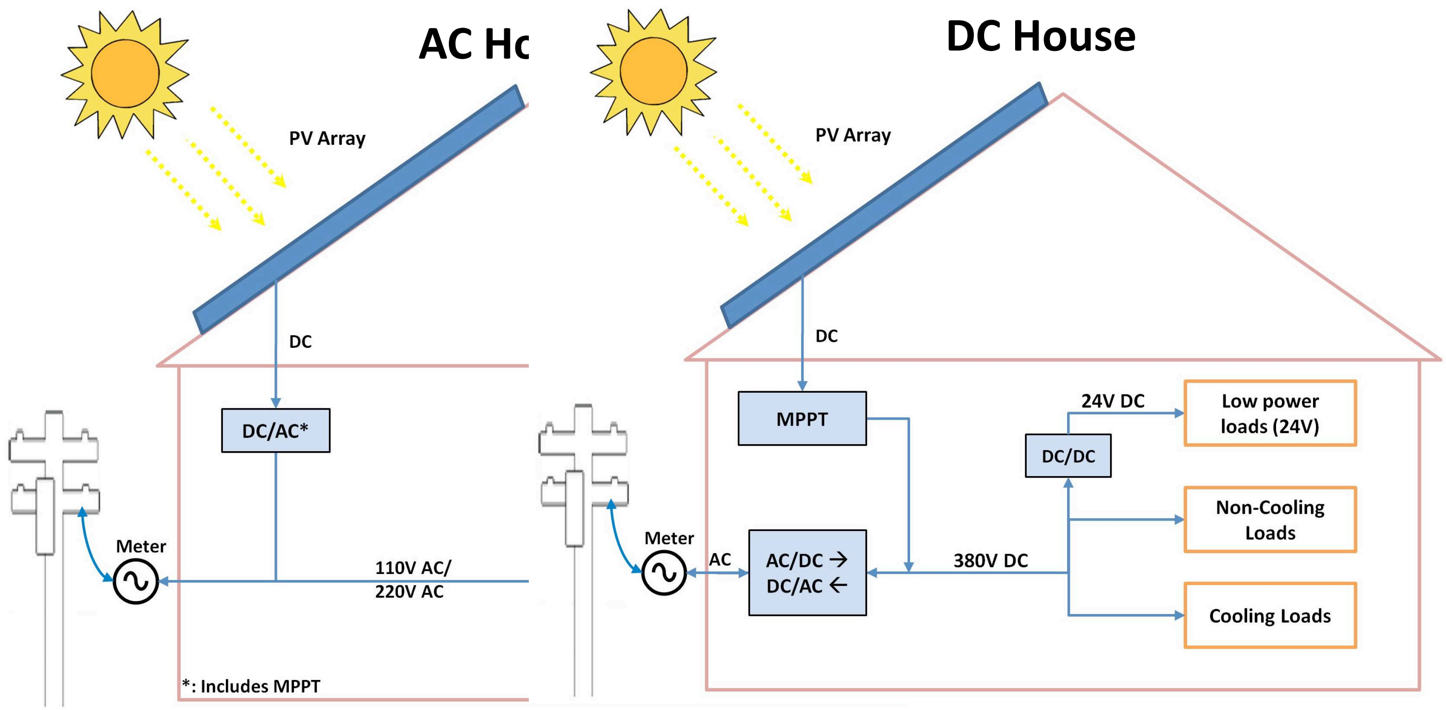
Distinguished cooling from non-cooling Loads

- Cooling load: Most significant load, influenced by solar irradiance
- Load shifting analysis: 2-hr shift (pre-cooling, house = thermal storage)

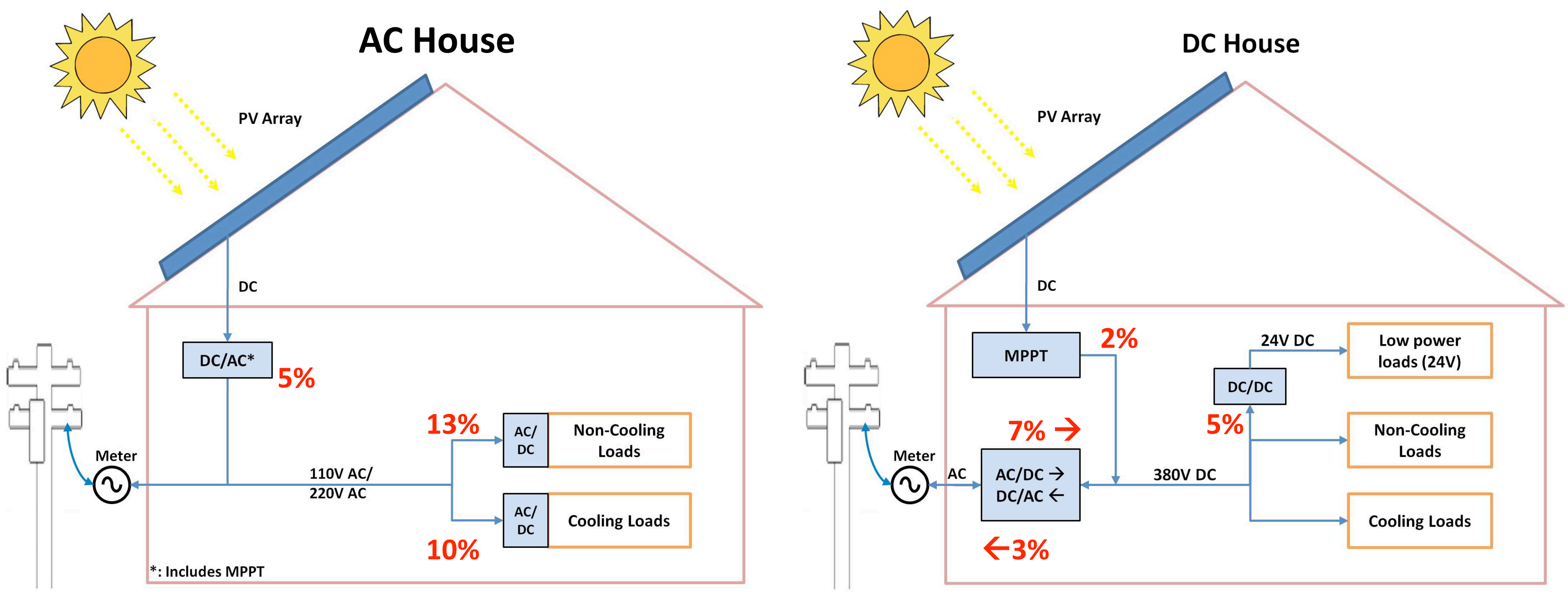


AC-house versus DC-house energy Use

- PV system sized for **<u>zero-net</u>** electricity in the AC-house
  - Same PV system on the DC house
- AC and DC-house loads **<u>identical</u>**, except for power converters.



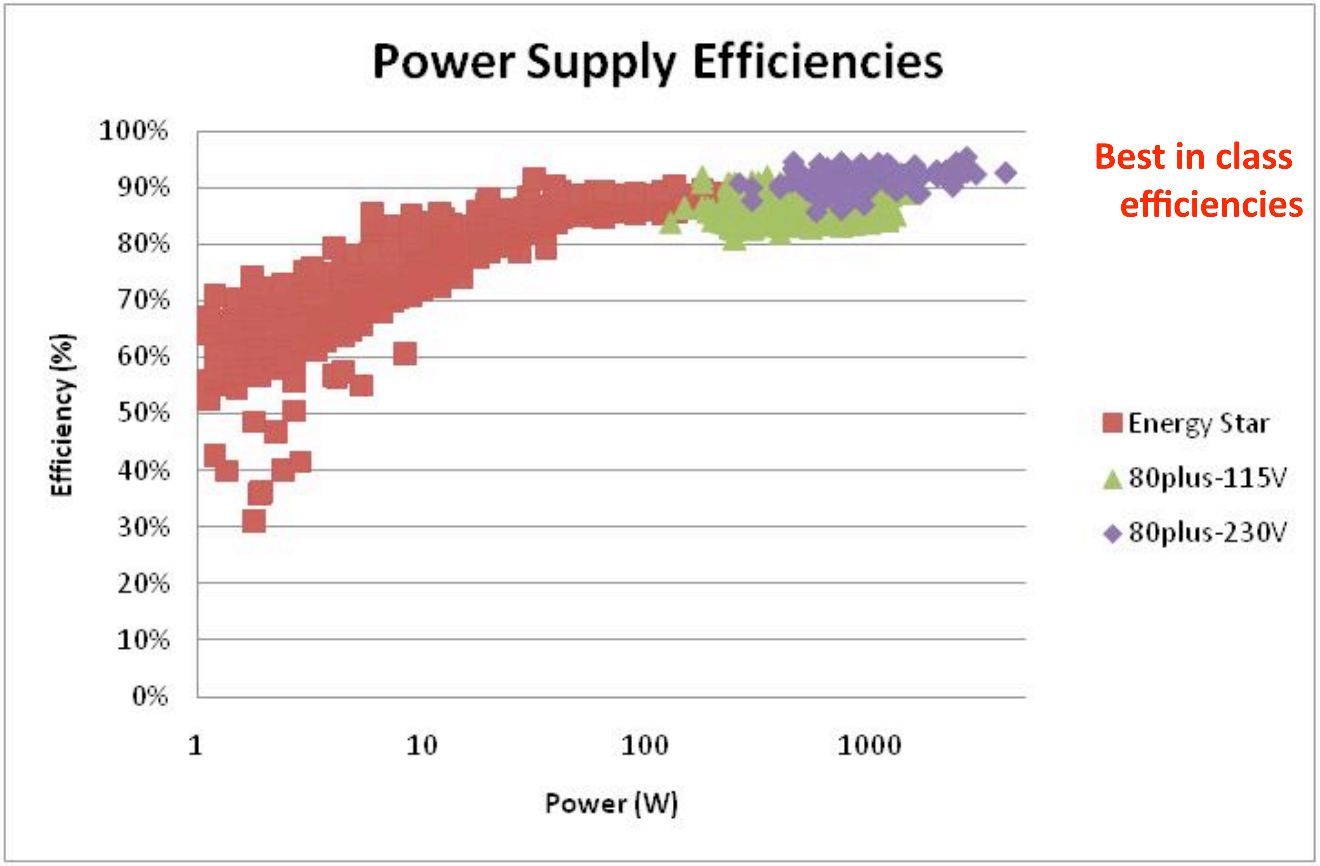
Power losses (Conversion efficiencies)



Sources of power loss data

- Power system components: CEC data, Equipment spec sheets, Industry experts
- Appliance AC-DC Converters: Energy Star, 80plus data

Example: Appliance converter data



Note on power converters

- Their efficiencies vary for full-load versus partial-load conditions
- Model assumes:
  - full-load for base case and
  - partial load for sensitivity analysis

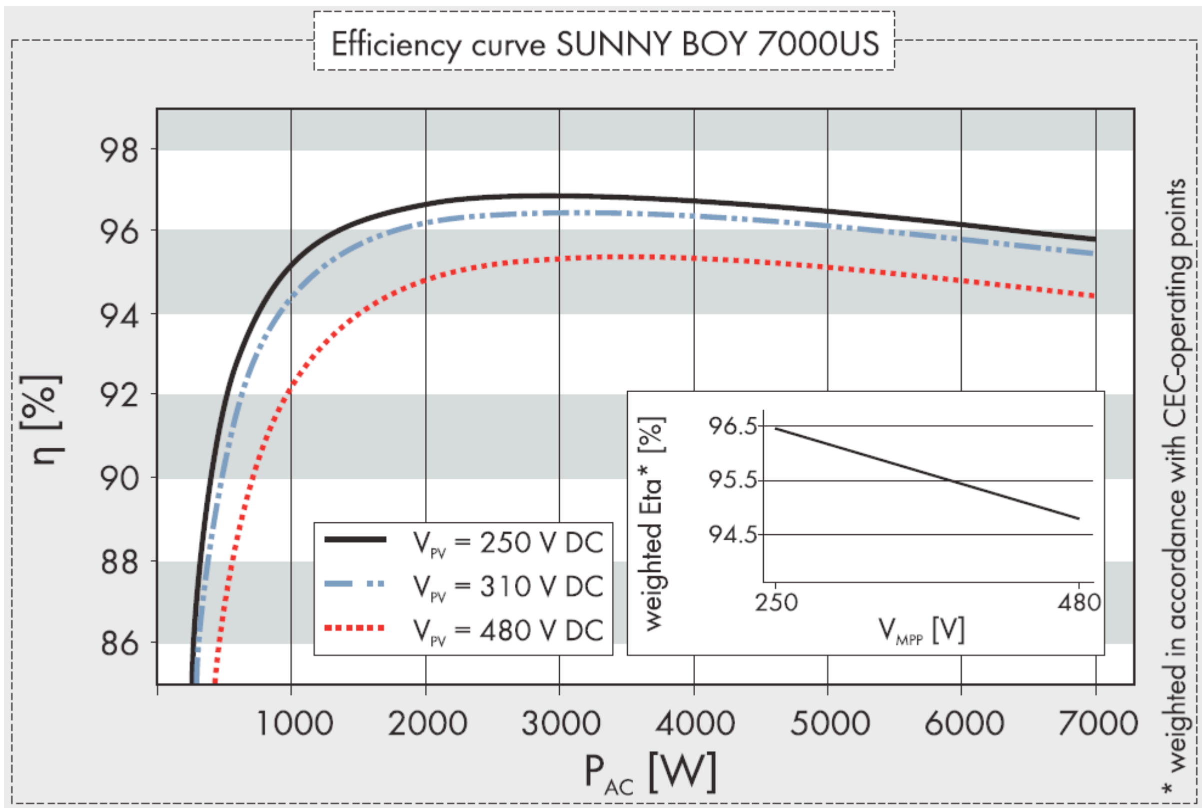


Photo courtesy of SMA-America

House loads modeling

- Identical loads for AC & DC house (except AC-DC converters)
  - Assumed DC-internal appliances in AC-house
  - Since DC loads are generally more efficient, we modified today's AC load to reflect those savings
  - DC-house load = DC-part of AC-house load
    - Subtracted off AC-DC conversion efficiencies
  - Used aggregate loads for model input
    - Cooling
    - Non-cooling
      - High and low voltage for DC house

Appliance analysis for model inputs (running on AC)

- To determine what end-uses can run on DC, we identified DC-based technologies that provide the internal functions within appliances
- Determined energy savings inherent in switching to DC
- Considered 32 household end-uses

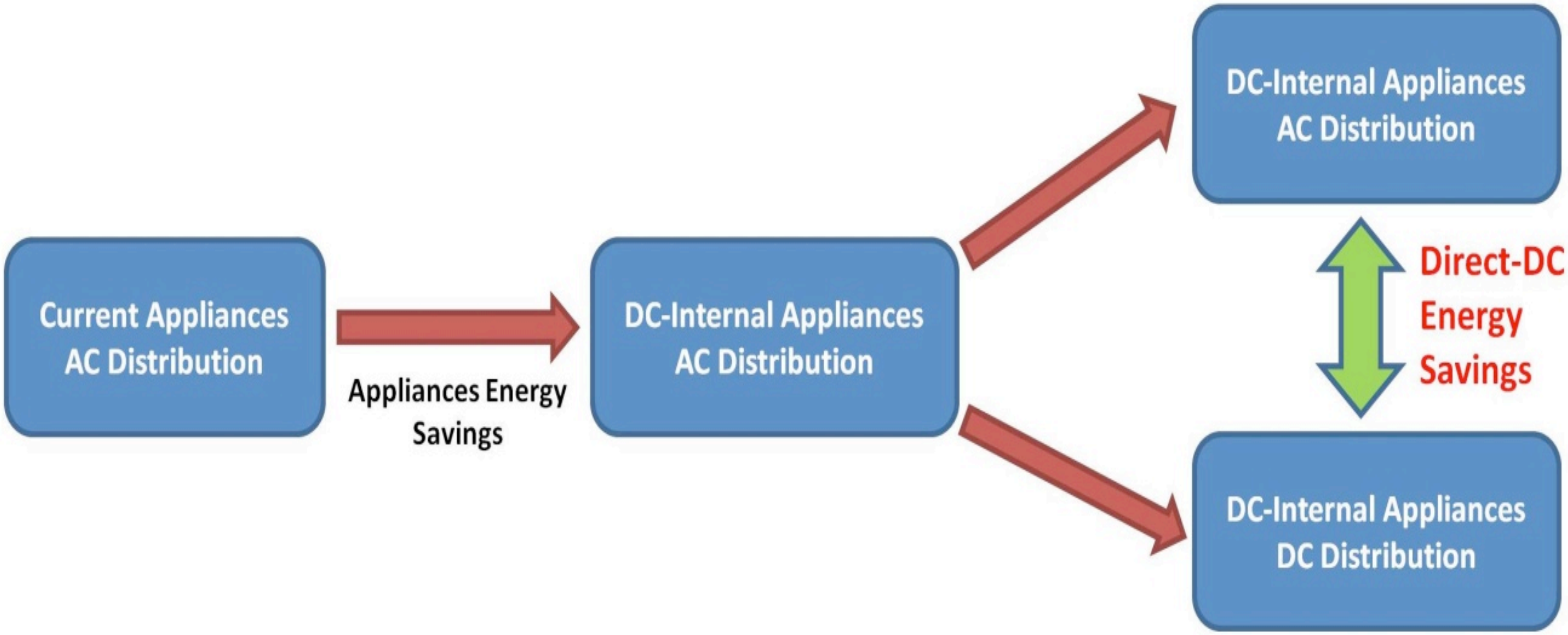
Functions w/in Appliances	DC-Internal Best Technology	Energy Savings relative to Standards
Lighting	Electronic (fluorescent & LED)	73%
Heating	Heat pump operated by BDCPM (for space and water)	50%
Cooling	BDCPM operating variable speed	30% – 50% (for VSD) 5-10% (motor, depending on size)
Mechanical work (fluids or solids)	BDCPM	5 – 15% (depending on size)
Cooking	Induction cooker	12%
Intelligence (computation)	Same	0

Notes: BDCPM = brushless DC permanent magnet motor; VSD = variable speed drive

Model runs

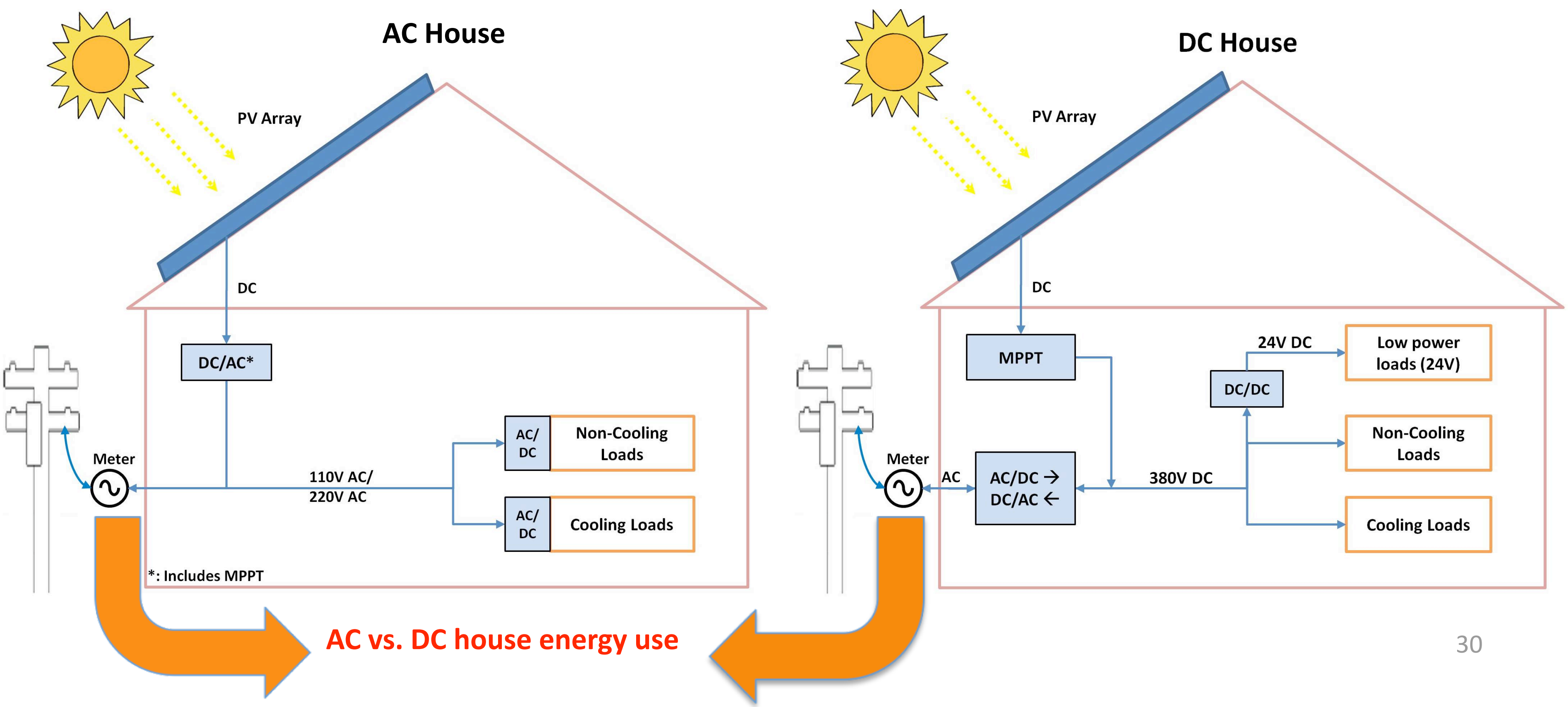
- Switch to more efficient, DC-internal appliances:
  - All end-uses can run on DC
  - 37% energy savings for cooling loads (weighted average)
  - 33% energy savings for non-cooling loads (weighted average)

- Direct-DC energy savings exclude the savings from switching to DC-internal appliances other than the AC-DC power conversion



How the model calculates savings

- Deterministic spreadsheet model
- Tracks the hourly impact of net electricity at the electric meter for both houses
- The reported energy savings are the direct-DC savings as percent of total AC- house load for each city



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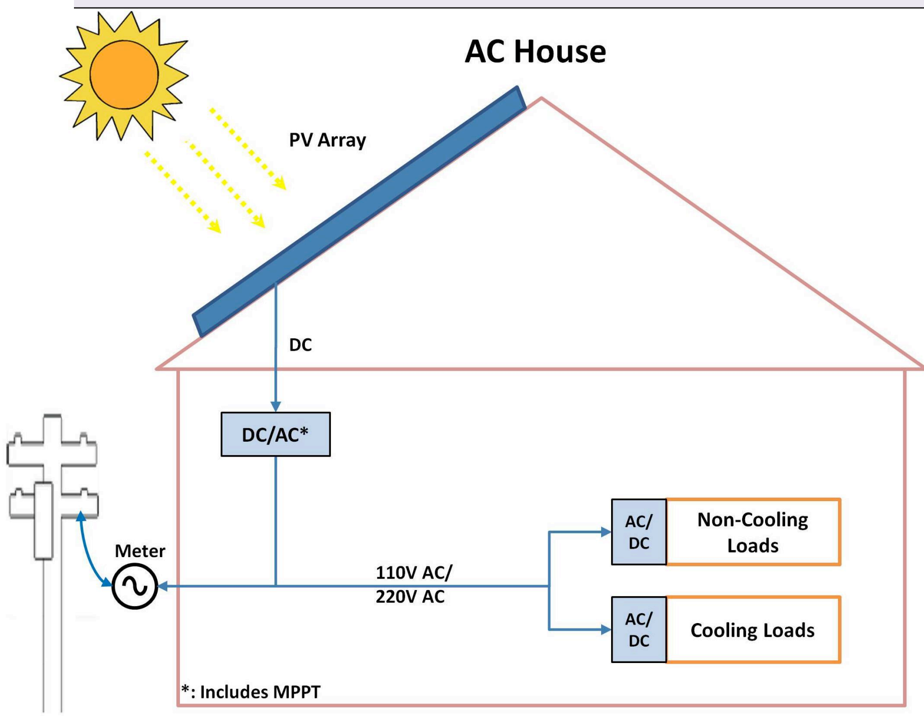
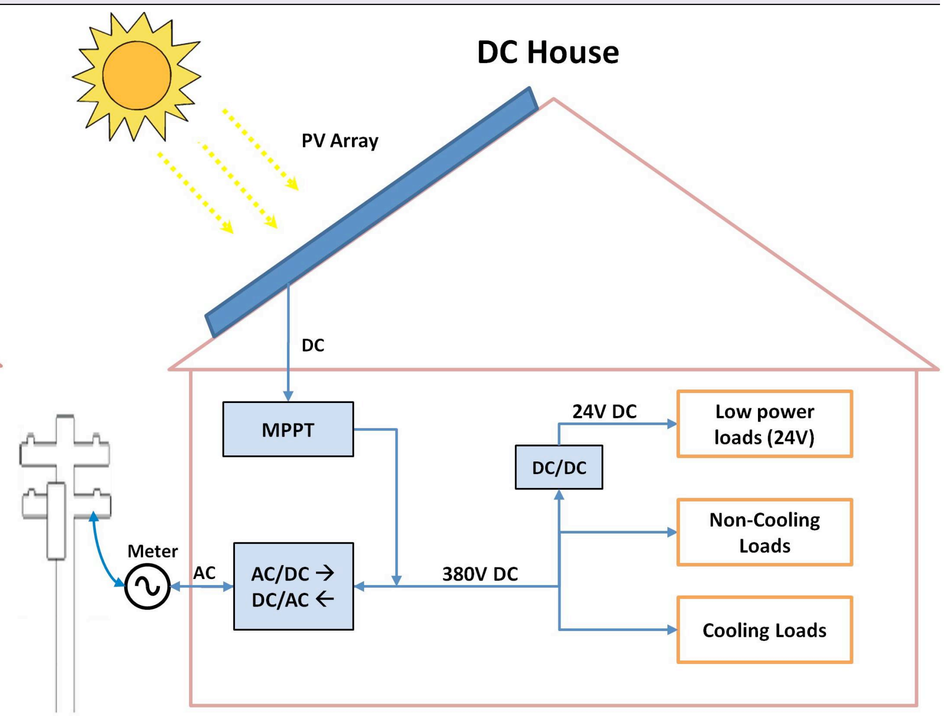
Six house configurations

Base Case Configurations

Without electricity storage	With electricity storage
1a. Average residential load	**1b**. Average residential load

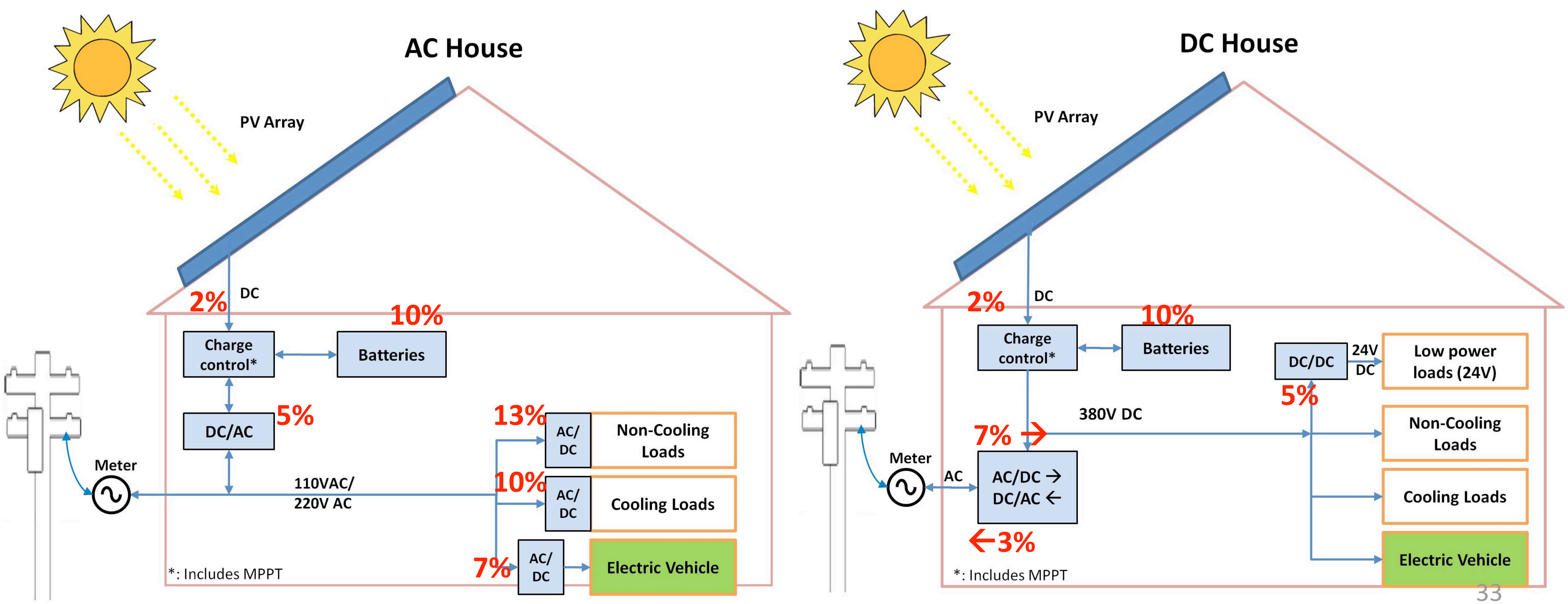




Configurations with storage, load shifting & electric vehicle

ASSUMPTIONS

- Battery only charged by PV
- EV acts only as a DC load (EV battery does not provide storage for house)
- Battery and EV charging voltage: 380V-DC
- Load shifting : Pre-cool by 2hrs



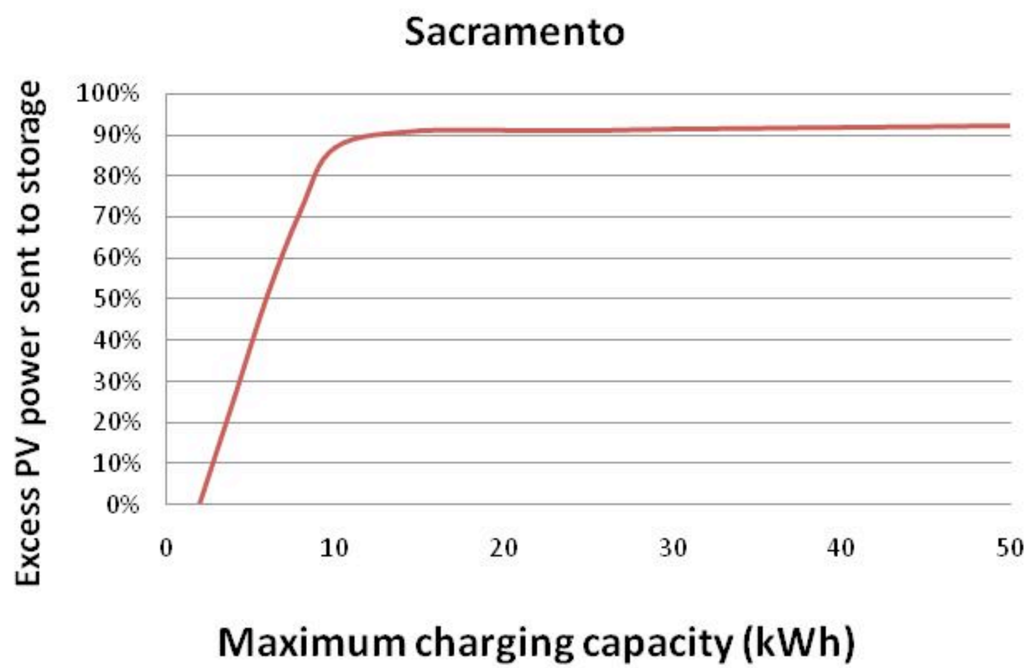
Electric vehicle & storage assumptions

Electric vehicle:

- EV battery capacity based on Nissan Leaf (24kWh)
- 8 kWh average charging each night
- Charging occurs at night (10 pm – 5am)
- The PV system size remains the same (no longer net-zero energy AC-house)

House storage system:

- Minimum charge: 2kWh
- Maximum charge: 10kWh



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Average residential load without (1a) & with storage (1b)

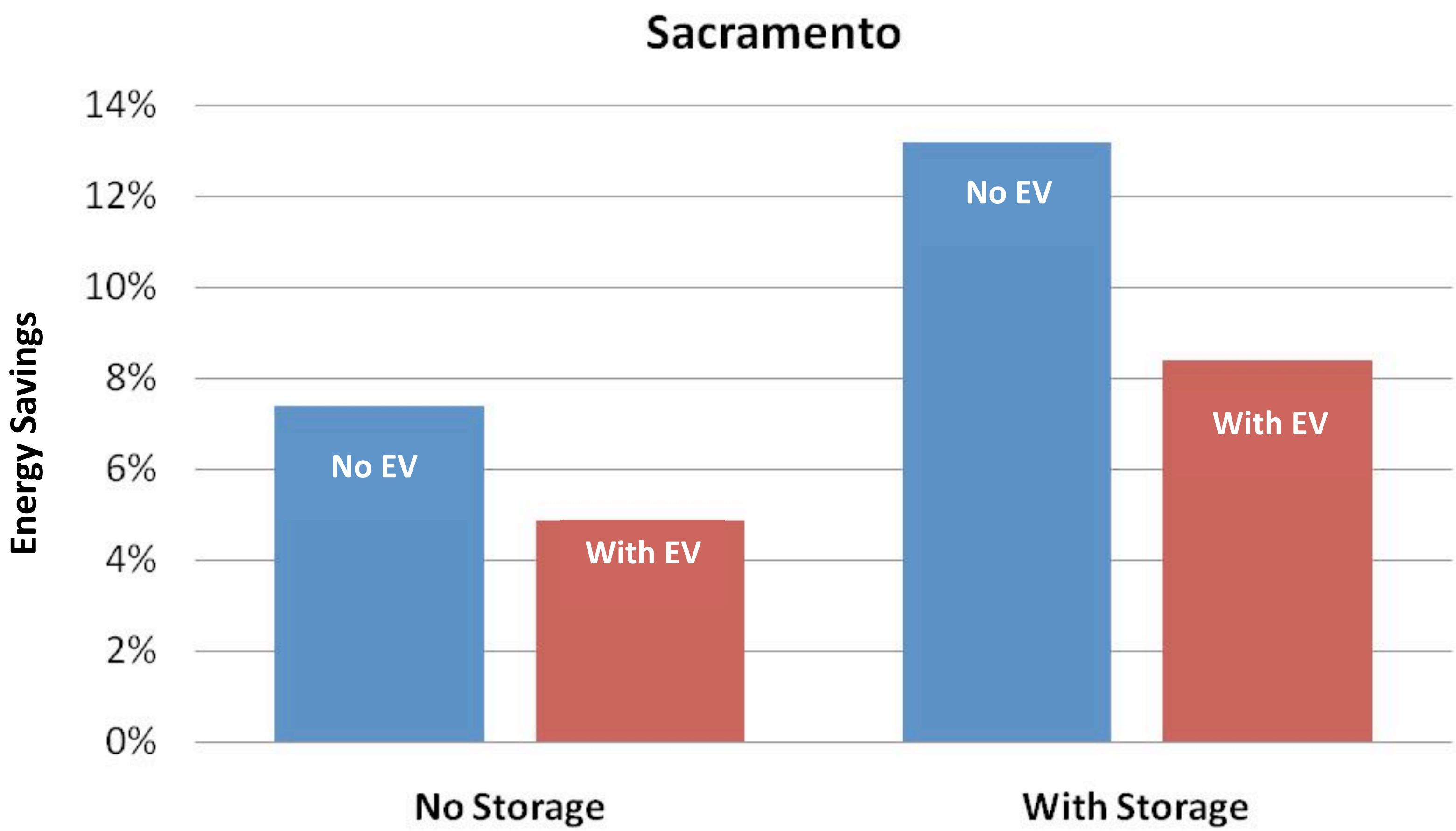
		DC DIRECT SAVINGS AS PERCENT OF TOTAL AC HOUSE LOAD	
CITIES	**Cooling Load Fraction**	**No-storage**	**Storage**
Phoenix	66%	7.6%	11%
Tampa	56%	8.0%	12%
Houston	48%	7.9%	12%
Fort Worth	43%	7.6%	12%
Sacramento	32%	7.4%	13%
Atlanta	28%	7.5%	13%
Lexington	17%	7.4%	13%
Medford	17%	7.2%	13%
Los Angeles	15%	7.3%	14%
New York	11%	7.3%	14%
Denver	10%	7.2%	14%
Helena	9%	7.2%	13%
Chicago	8%	7.2%	13%
Seattle	3%	7.0%	13%
	AVERAGES:	**7.4%**	**12.8%**

Average residential load without (2a) & with storage (2b)

Cooling load shifted 2hrs earlier

		DC DIRECT SAVINGS AS PERCENT OF TOTAL AC HOUSE LOAD	
CITIES	Cooling Load Fraction	Non-storage	Storage
Phoenix	66%	8.3%	11%
Tampa	56%	8.5%	12%
Houston	48%	8.3%	12%
Fort Worth	43%	8.2%	12%
Sacramento	32%	8.2%	13%
Atlanta	28%	8.0%	13%
Lexington	17%	7.8%	13%
Medford	17%	7.6%	13%
Los Angeles	15%	7.6%	13%
New York	11%	7.5%	14%
Denver	10%	7.4%	14%
Helena	9%	7.4%	13%
Chicago	8%	7.4%	13%
Seattle	3%	7.1%	13%
	AVERAGES:	**7.8%**	**12.9%**

Average residential load with EV without (1a vs. 3a) & with storage (1b vs. 3b)



Because EV is assumed to be charged at night it is not a direct DC load, therefore reduces **fractional (not absolute)** direct-DC savings

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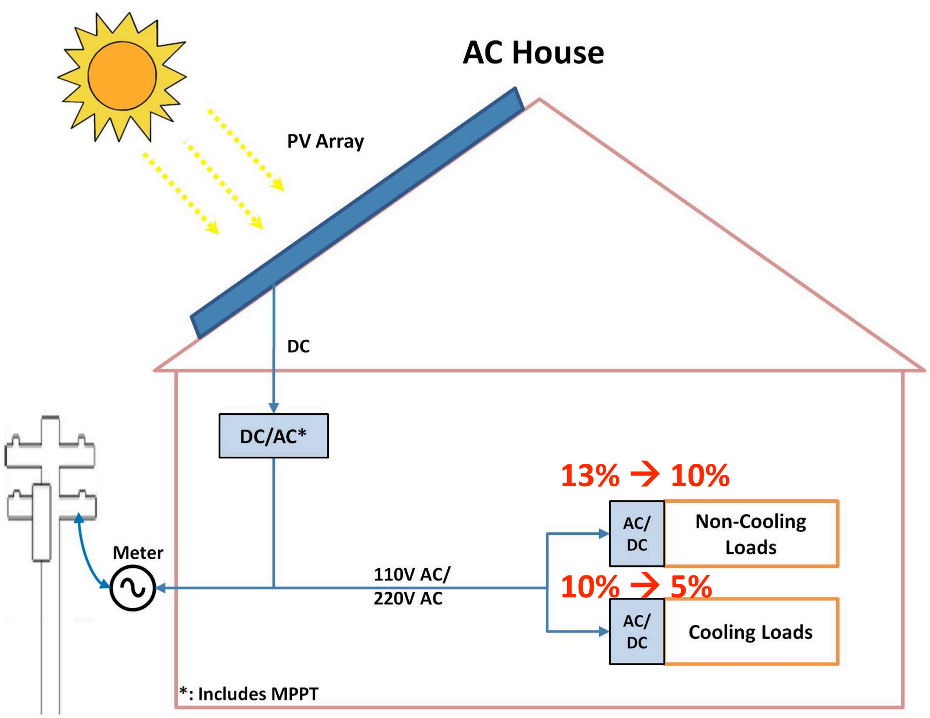
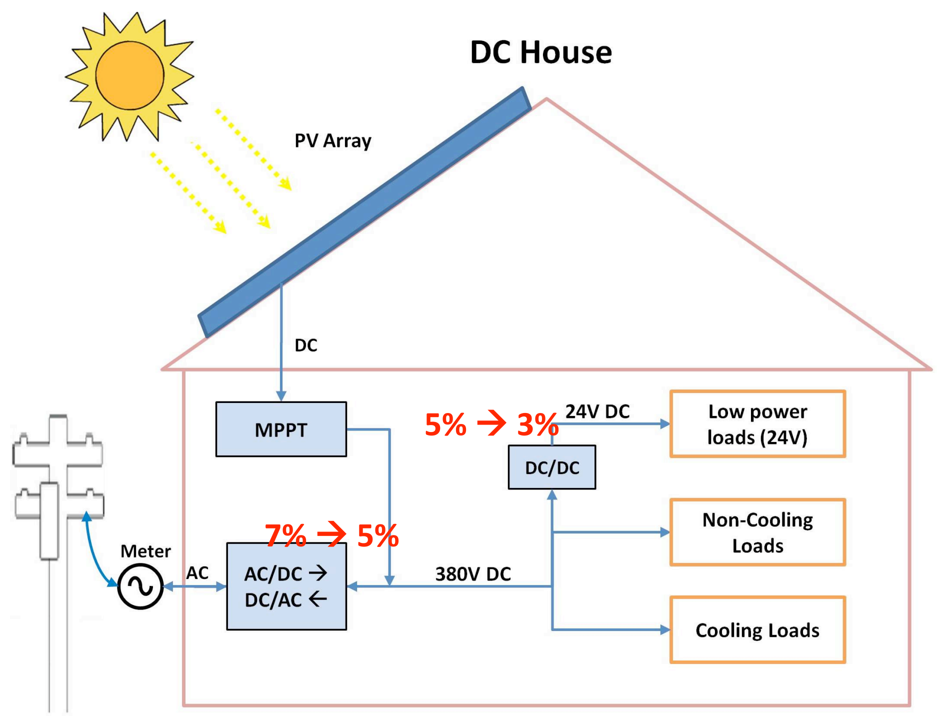
1. Consider technology Improvements

A. Improve AC-house AC/DC appliance converters efficiencies

B. Improve DC-house power converter efficiencies

NO STORAGE





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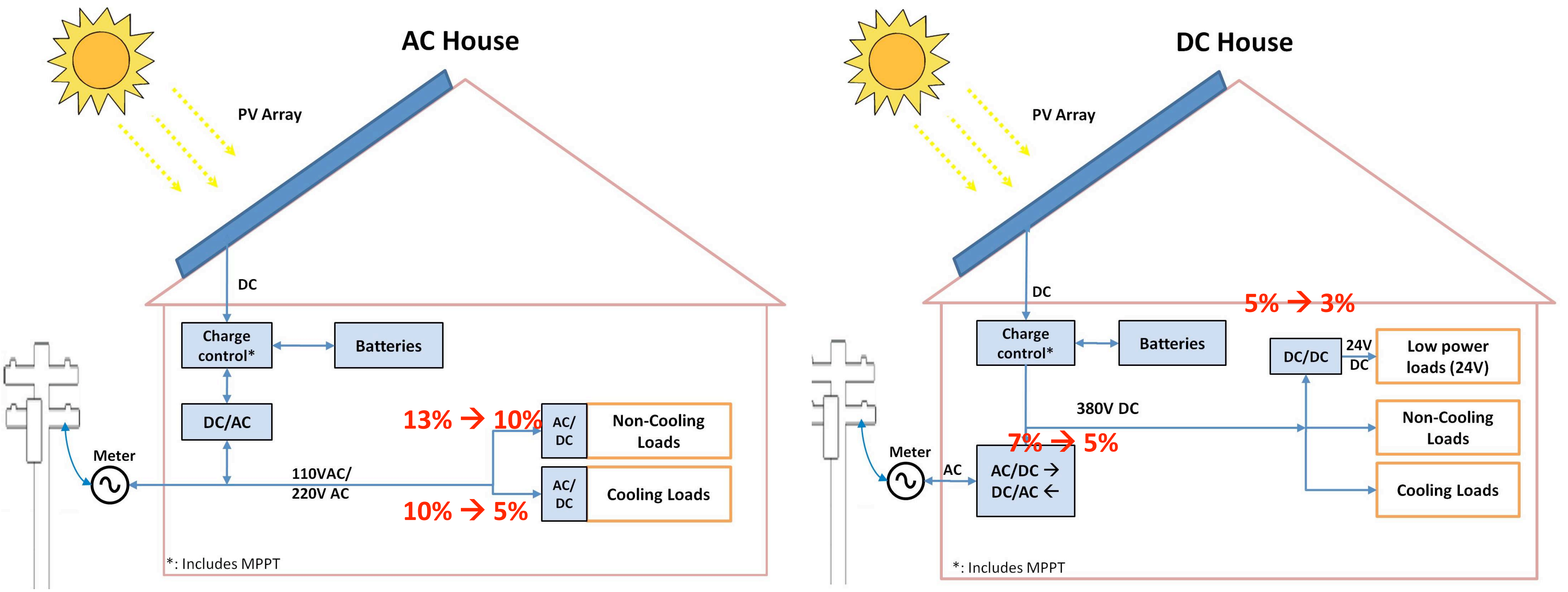
WITH STORAGE

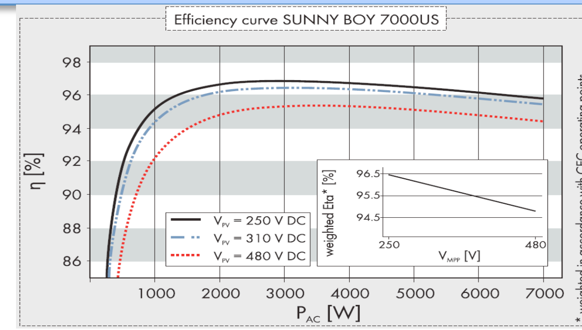


1. Consider technology Improvements

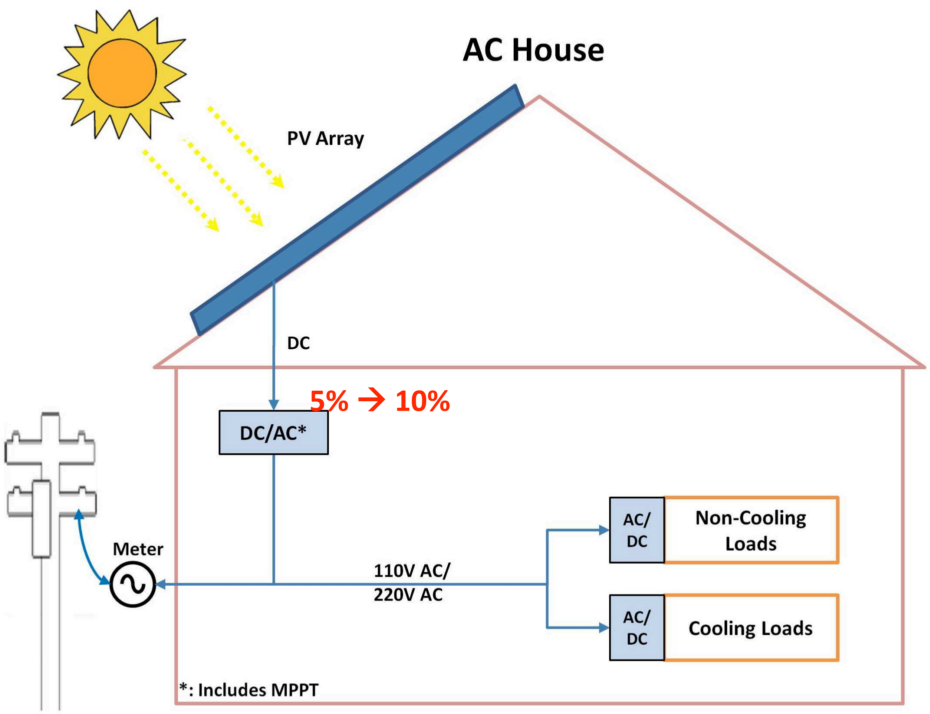
	Efficiencies	Non-storage savings	Storage savings
	Base case efficiencies	**7.4%**	**12.8%**
A.	Improve DC-house power converter efficiencies	9.3%	13.7%
B.	Improve AC-house AC/DC appliance converters efficiencies	4.0%	9.3%

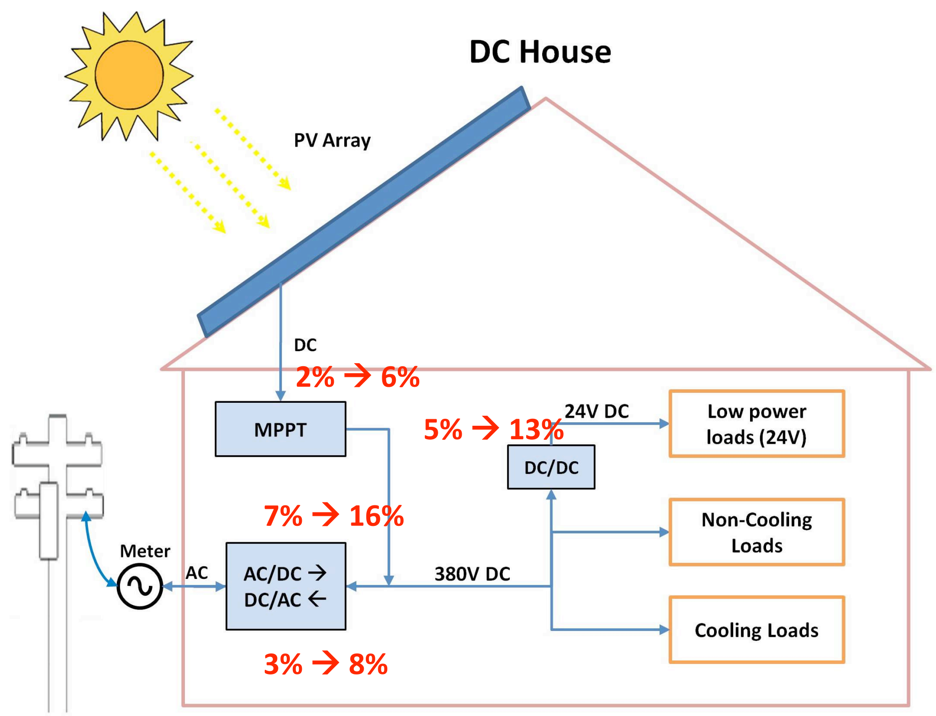
➢ **Given that technology improvements are likely to proceed together, the relative effects are likely to cancel each other out.**

2. Consider Partial Load Conditions



NO STORAGE





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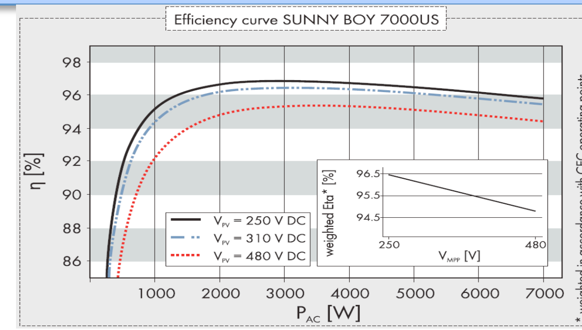

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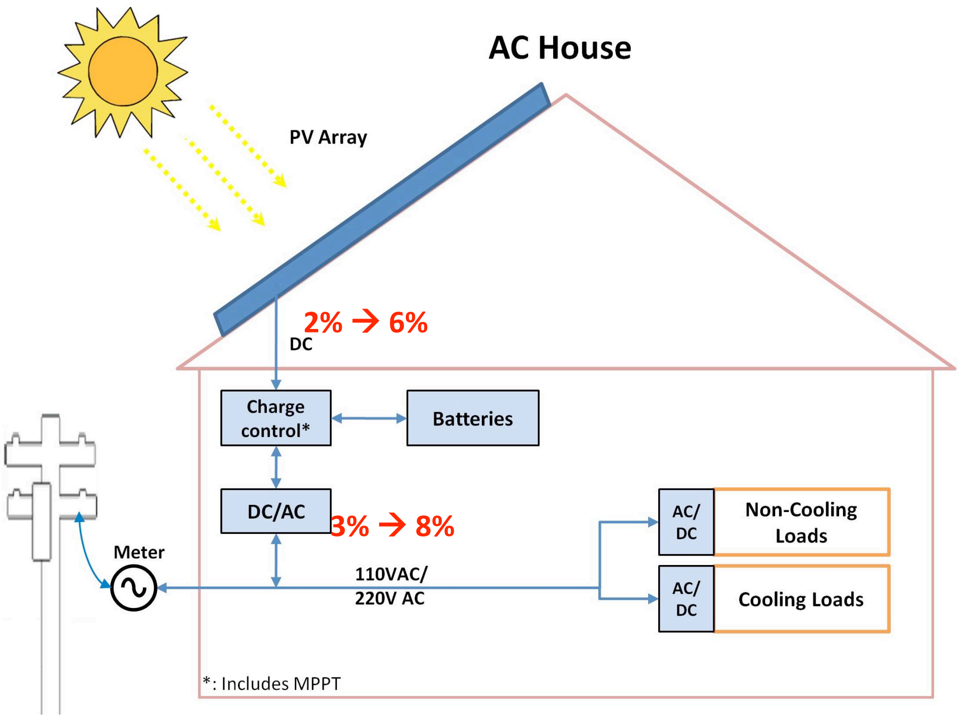

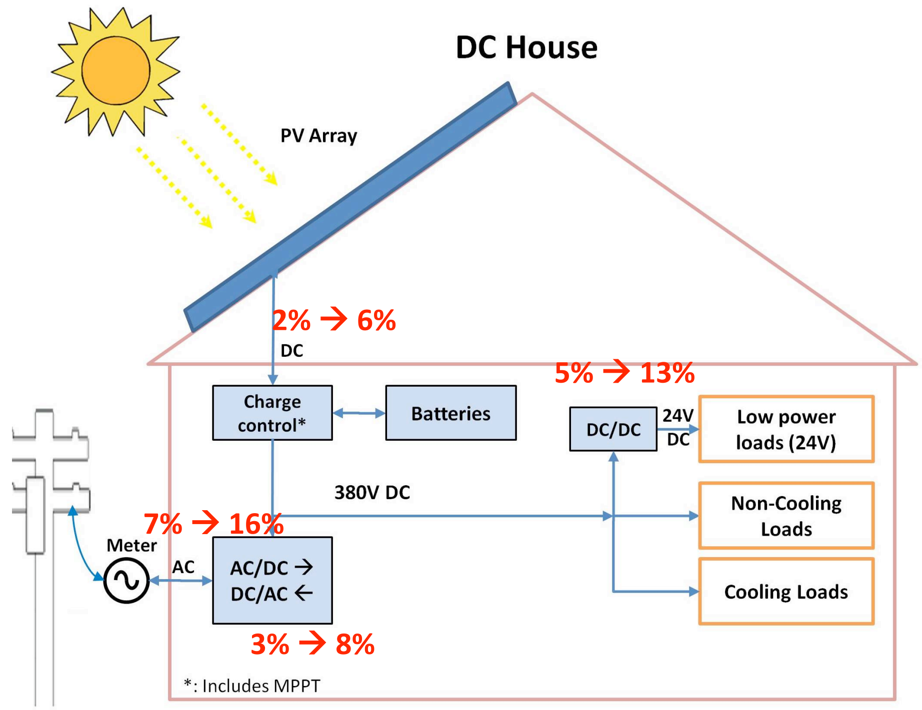

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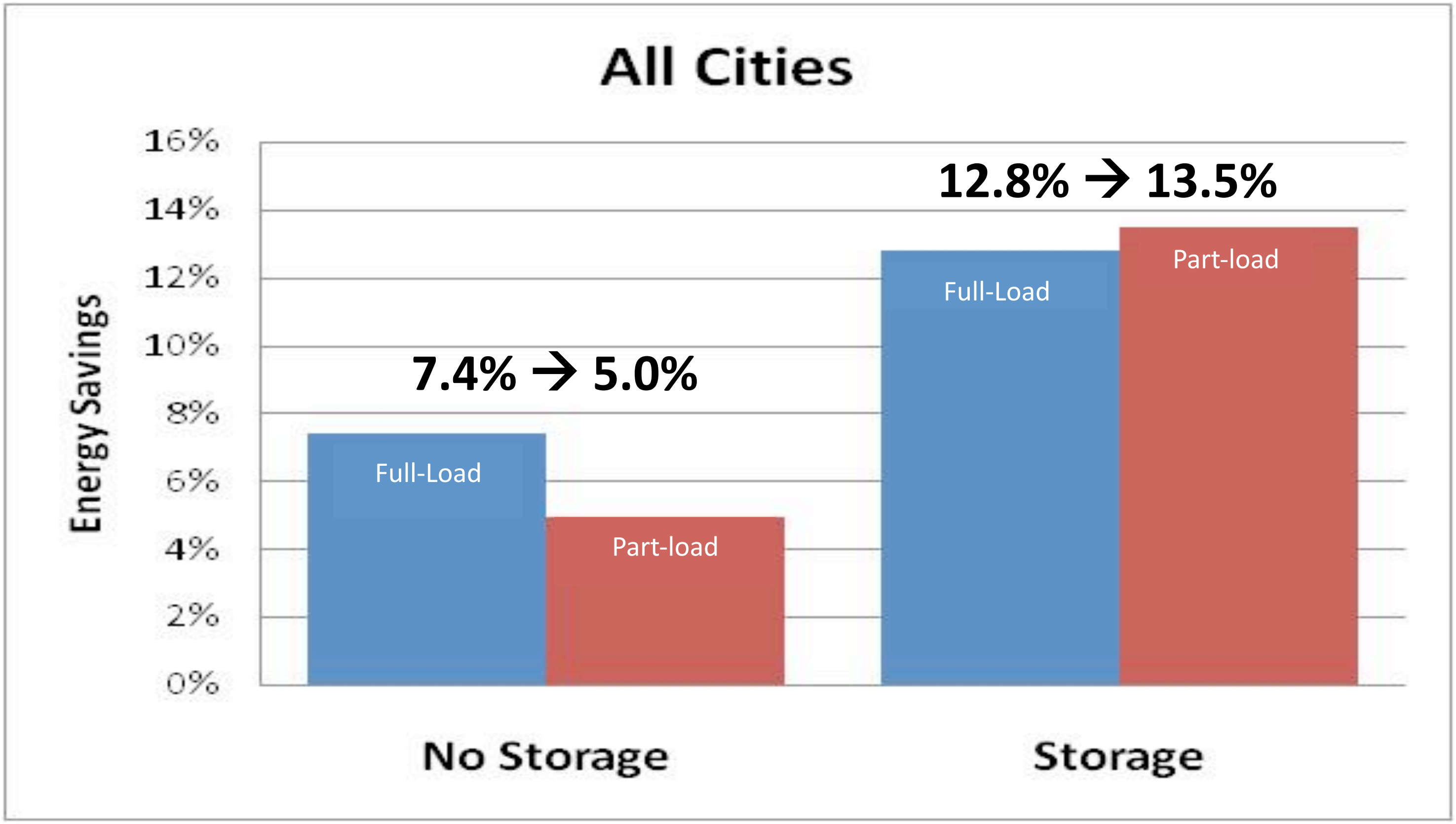

(more realistic estimate)

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Conclusions

<u>The following had a negligible effect on Direct-DC savings:</u>

– Climate

– Load shifting

– EV load (assuming night-time charging)

<u>What did matter</u>

– Timing of load versus insolation

- high potential for large daytime loads
- space cooling and daytime EV charging (commercial)

– Relative conversion efficiencies

- of the AC and DC power system components and the load

– Part load efficiencies

Major Findings

- Essentially all end-uses are DC-compatible
  - Switching to DC-internal appliances will result in major savings ~35% (whether they are run on AC or DC)
  - Trend is already occurring
- Direct-DC could save energy in net-metered houses with PV
  - Modest without storage (~5%).
  - Meaningful with storage (~9% or more)

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Discussion

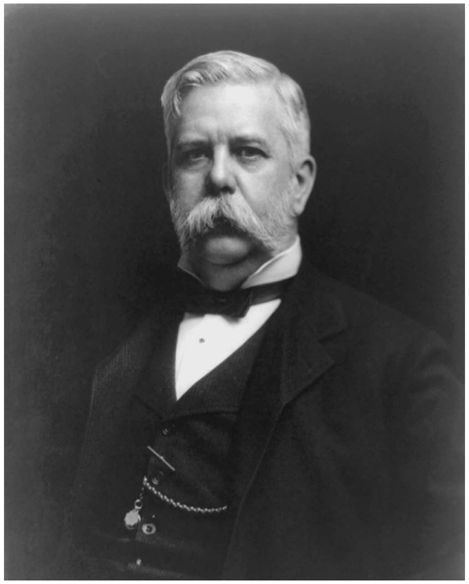
- Results consistent with but not directly comparable with the results of others
  - Baek et al 2010 (University of Seoul) 1-3% savings
    - Considered temporally variable load, but not net-metered
  - Savage et al 2010 (Yale Study) 25% savings
    - Considers portion of load, some DC-internal, not timing
  - Arthur D Little 2010 (NEDO, Japan) 5 – 25% savings
    - Various scenarios of implementation including controls and DC-internal effects

Discussion

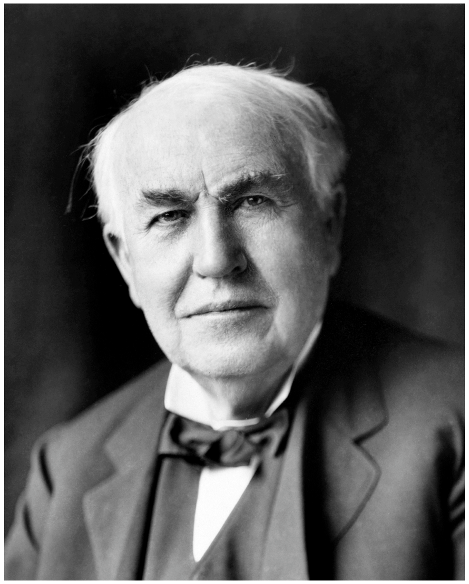
Priorities for Future Work

- ➢ Model commercial sector (larger direct-DC savings, better coincidence between sun and load)
- ➢ Better load simulation (real loads are spiky and timing of load matters)—should reduce estimated savings potential

To be continued?



AC/DC



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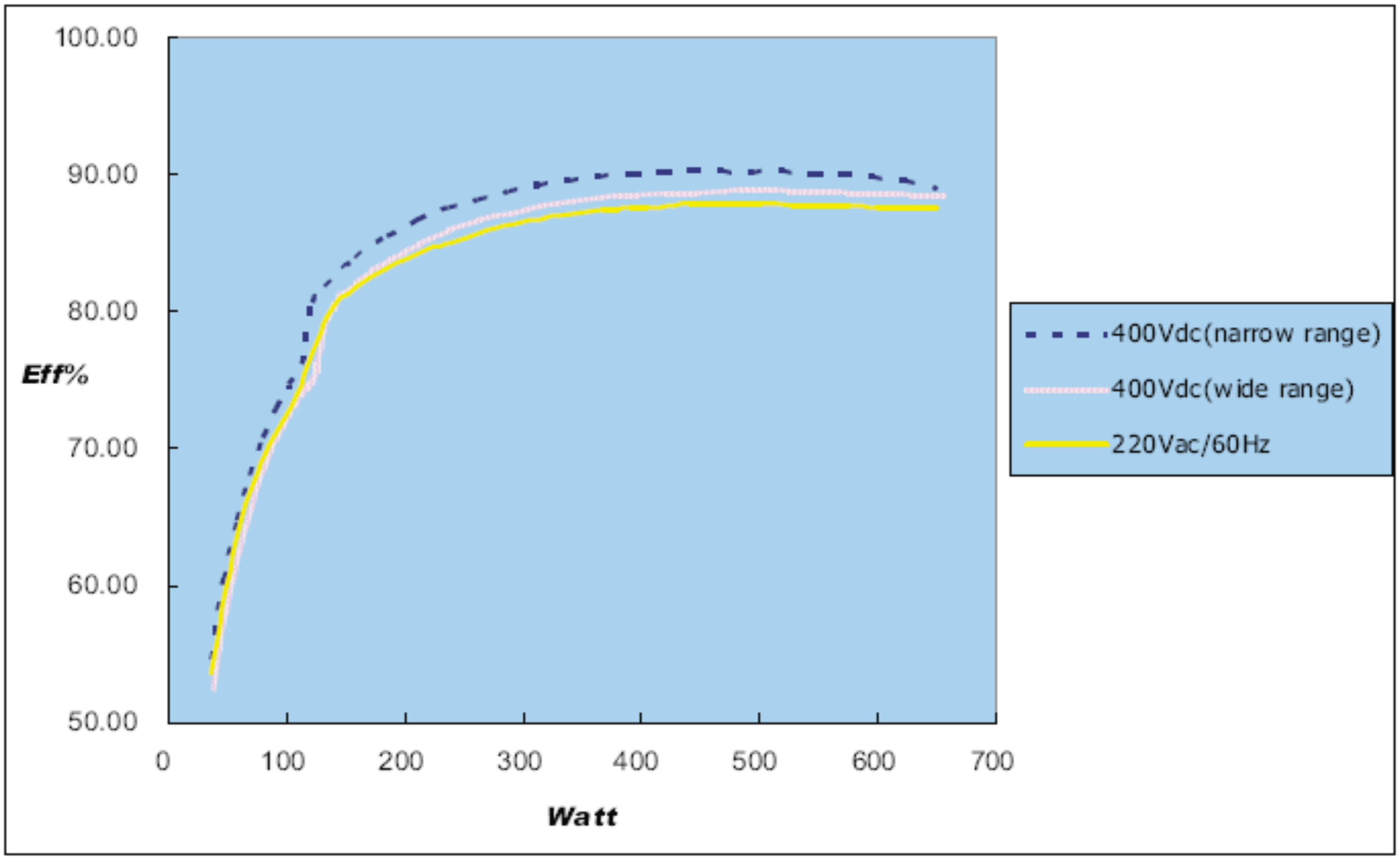
ADDITIONAL INFORMATION

Storage System Performance in the AC and DC Houses

#	CITIES	Cooling load fraction	Percent of time storage is at minimum capacity		Percent of time storage is at maximum capacity		Percent of non-coincident with PV loads serviced by storage		Percent of excess PV power sent to storage	
			AC	DC	AC	DC	AC	DC	AC	DC
1	Phoenix	66%	33%	28%	18%	21%	42%	46%	54%	48%
2	Tampa	56%	34%	27%	12%	16%	57%	65%	73%	65%
3	Houston	48%	32%	24%	13%	15%	57%	66%	73%	67%
4	Fort Worth	43%	30%	21%	11%	13%	58%	68%	74%	70%
5	Sacramento	32%	32%	22%	6%	9%	68%	78%	87%	80%
6	Atlanta	28%	25%	16%	6%	9%	68%	79%	87%	81%
7	Lexington	17%	27%	17%	6%	8%	68%	80%	88%	81%
8	Medford	17%	34%	23%	9%	10%	63%	73%	81%	75%
9	Los Angeles	15%	26%	14%	3%	5%	74%	86%	95%	88%
10	New York	11%	25%	15%	4%	7%	72%	82%	92%	84%
11	Denver	10%	24%	13%	5%	7%	73%	85%	94%	87%
12	Helena	9%	28%	20%	8%	11%	64%	73%	82%	75%
13	Chicago	8%	28%	17%	7%	9%	67%	77%	86%	79%
14	Seattle	3%	29%	24%	8%	10%	60%	64%	77%	67%
AVERAGES:			**29%**	**20%**	**8%**	**11%**	**64%**	**73%**	**82%**	**75%**
Standard Deviation			**3%**	**5%**	**4%**	**4%**	**8%**	**11%**	**11%**	**11%**

DC/DC Power Supply Efficiency Curve



Appliance	kWh/yr in 2010	Assumed Replacement Technology	Energy Savings	AC-DC Conv.Eff
Central Air Conditioners (SEER)	1328	DC motor with variable speed compressor and fans	47%	89%
Room Air Conditioners (EER)	235	DC motor with variable speed compressor and fans	34%	89%
Electric Heat Pumps (SEER) AC	355	unchanged	0%	88%
Geothermal Heat Pumps for AC	10	unchanged	0%	88%
Electric Clothes Dryers	677	heat pump	50%	89%
Electric Secondary Space Heaters	68	unchanged	0%	89%
Dishwashers	232	controls and DC compatible motor	51%	88%
Electric Water Heaters (EF)	1128	heat pump	50%	88%
Other Electric Space Heaters	463	heat pump	50%	88%
Spas	72	heat pump	50%	88%
Electric Cooking Equipments 5/	273	Induction cooktops	12%	88%

Electric Heat Pumps (HSPF) for Heating	**185**	**unchanged**	**0%**	**88%**
Geothermal Heat Pumps	7	unchanged	0%	88%
Solar Water Heaters	3	unchanged	0%	88%
Refrigerators (kWh per year 6/)	930	assuming 85% standard-size @587kWh AEU has EURF 0.49 and 15% compact @331kWh AEU has EURF 0.25	53%	87%
Freezers (kWh per year 6/)	199	assuming 80% standard-size @565kWh AEU has EURF 0.47 and 20% compact @246kWh AEU has EURF 0.48	53%	87%
Furnace Fans and Boiler Circulation Pumps	366	Brushless DCPM variable speed	30%	87%
Ceiling Fans	158	Brushless DCPM variable speed motor	30%	87%
Clothes Washers	83	Brushless DCPM variable speed motor	30%	87%
Electric Other	1468	unchanged	0%	87%

Microwave Ovens	**114**	**unchanged**	**0%**	**87%**
Coffee Makers	36	unchanged	0%	87%
Color Televisions and Set-Top Boxes	938	unchanged	0%	85%
Security Systems	17	unchanged	0%	83%
Lighting-Incandescent	1370	14LPW goes to CFL (electronic ballast) @52LPW	73%	82%
Lighting-Reflector	216	15LPW goes to CFL (electronic ballast) @52LPW	71%	82%
Lighting-Torchiere	89	assuming 80% incandescent @14LPW goes to CFL @52LPW and 20% CFL stays the same	69%	82%
Lighting-Fluorescent	148	assuming 10% linear @83LPW goes to 100LPW and 90% CFL @52LPW stays the same	1%	82%
Personal Computers and Related Equipment	473	unchanged	0%	80%
Rechargeable Electronics	78	unchanged	0%	80%
Home Audio	100	unchanged	0%	79%
DVDs/VCRs	217	unchanged	0%	69%